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ON THE DEVELOPMENT OF A MESOSCALE WIND FIELD MODEL

Report No 86-248-K

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ABSTRACT

Mesoscale meteorological phenomena cover a wide range of horizontal spatial and temporal scales from a few to several hundred kilometers and one hour to several days, respectively. Within this scale, not only can severe weather have adverse social and economic impacts on human activity but other phenomena, such as lake-land breezes and complex terrain effects, are of considerable importance. Of special interest to Ontario Hydro is the mesoscale aspect of air quality in which the mesoscale wind and temperature fields play significant roles. This report presents a review and evaluation of some of the available numerical wind field models with respect to Ontario Hydro's requirements. It is concluded that a three-dimensional non-hydrostatic model with topographical effects meets most of Ontario Hydro's requirements to produce mesoscale wind and temperature fields.

job	file	date	report no.
740635-612-091	837.2212	September 16, 1986	86-248-K

Ontario Hydro

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Subject **Research Division Report 86-248-K**
"On the Development of a Mesoscale Wind Field Model"

This report documents our assessment of (1) mesoscale weather phenomena, (2) models which may be used to predict wind and temperature fields in the mesoscale, and (3) areas of potential application for these models within Ontario Hydro. While the study has identified a number of applications, it is not at all clear that we should proceed with the next step, the preparation of a strategy and procedure leading to the development and implementation of a mesoscale model. In particular, the application in nuclear contingency management, which largely motivated this assessment, is being discussed by the Province and Ontario Hydro (RMEP). This report may prove valuable in those discussions. At the same time, we will continue to gauge the level of interest within Ontario Hydro for a mesoscale model and, if justified, proceed to the next phase.

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EXECUTIVE SUMMARY

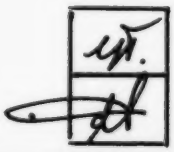
ON THE DEVELOPMENT OF A MESOSCALE WIND FIELD MODEL

Y.T. Tam

This report is concerned with the development of suitable numerical models for the prediction of mesoscale wind and temperature fields. The report begins with a description of the background information and defines the objectives (Section 1.0). These are followed by an extended discussion of the wide variety of potential applications of such models within Ontario Hydro (Section 2) and of the physical processes which determine the mesoscale wind field (Section 3.0). Some recent models are then reviewed briefly in terms of their dynamic structure, computer requirements and applicability (Section 4.0).

The models reviewed are Sherman's mass conservative model, Pielke's sea-breeze model, Tapp and White's non-hydrostatic model, Bornstein's vorticity-streamfunction model, NCAR's mesoscale model, OME's wind field model and Lee and Kau's complex terrain model. All of the models are three-dimensional and have been described in the open literature. Each model has a different conceptual structure and level of detail.

The models are evaluated and proposed modifications are presented (Section 5.0). A three-dimensional non-hydrostatic model, incorporating the effects of varying topography, is considered the most attractive of all models for implementation and development. If non-hydrostatic effects are not important, a three-dimensional hydrostatic model with topographical effects or an objective analysis model using variational techniques may be adapted.



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Dr. D. Mills
Director of Research

ON THE DEVELOPMENT OF A MESOSCALE WIND FIELD MODEL

1.0 INTRODUCTION

1.1 Background

In the traditional threefold classification of atmospheric systems, the mesoscale is the link between the macroscale synoptic motions and the microscale local weather. It has a horizontal spatial scale ranging from the order of a few kilometers to several hundred kilometers or so and a temporal scale ranging from about one hour to several days.

Atmospheric phenomena within the mesoscale include fronts, hurricanes, jet streams, cloud clusters, rainbands, squall lines, convective complexes and the disturbances induced by land-lake interfaces, complex terrain features and urban effects. These mesoscale phenomena have adverse social and economic impacts on human activity; also, they play significant roles on the transportation, diffusion and transformation of air pollutants in the atmosphere.

Ontario Hydro has particular interest in mesoscale atmospheric features because most of our power generating stations are located in lakeshore areas where mesoscale effects are likely to be important. For example, high-elevation emissions from the thermal generating stations could be fumigated to ground due to land-lake effects. The land-lake effect and local topographical features could complicate the path and behaviour (dispersion, deposition, etc) of the low-elevation emissions from the nuclear generating stations in the unlikely event of an accident. Emissions may also be re-distributed due to the diurnal variation of thermal convection and/or the presence of cloud systems. These are mesoscale processes. Moreover, the determination of source-receptor relationships in long-range transport requires information regarding the mesoscale flow. Mesoscale phenomena and complex terrain effects may also impact on the transmission and distribution system.

The structure and development of the mesoscale phenomena depend highly upon the distributions of atmospheric variables, especially the wind and temperature fields. Generally, the wind and temperature fields can be obtained by direct observations of sufficient spatial resolution or from synoptic weather analyses since the upper bound of the mesoscale is the lower bound of the synoptic macroscale. However, direct observations with reasonable resolution are very expensive. Synoptic weather data, on the other hand, are usually lacking in sufficient temporal and spatial resolution to define the mesoscale. Both approaches are of little practical use from the operational point of view.

An alternative approach, described here, is to use mathematical models. The dynamics of the mesoscale flows are expressed in mathematical form derived from the fundamental laws of hydrodynamics and thermodynamics, and solved numerically. The advantage of this approach is that once a model has been validated, it can be used to predict the needed information more efficiently and economically. Further, the model can be used to test the significance of various parameters affecting the mesoscale flow. This knowledge can be used in helping to formulate plans such as emission control strategies and nuclear contingency scenarios.

Numerous numerical mesoscale models have been developed in recent years. Predictions by these models are generally physically reasonable. However, each model has advantages and limitations in dealing with a particular application. It is often quite difficult to identify which model is superior. The objective of the present study is to examine if any of the available models, as they exist or with some modifications, can be used to provide wind and temperature fields suitable for Ontario Hydro's applications; and, if they cannot, to propose a model to meet such requirements and outline the design of such a proposed model.

1.2 Scope of the Present Study

In choosing a satisfactory model to predict mesoscale wind and temperature fields for Ontario Hydro's applications, the requirements of the applications must be grasped well. Some specific requirements are discussed in Section 2.0.

Section 3.0 describes those physical mesoscale processes which are of importance to Ontario Hydro. Practical model selection criteria and the review of some recent models are given in Section 4.0. Section 5.0 evaluates the reviewed models with respect to situations of interest to Ontario Hydro. Modifications are also suggested for the best of the available models in this section. Finally, concluding remarks are given in Section 6.0.

2.0 POTENTIAL APPLICATIONS OF MESOSCALE WIND FIELD MODELS WITHIN ONTARIO HYDRO

2.1 Assessment of Environmental Impact

Quantitative assessment of the potential environmental impact is required for the design, licensing and operating of a facility. At Ontario Hydro, such assessments are performed by groups including the Design and Development, Health and Safety, Power System Operations, Thermal and Hydraulic Generation, Technical and Training Services, Nuclear Generation and Research Divisions.

Different groups have different modelling requirements. For example, the maximum ground-level concentration of pollutants and estimated dosage in the vicinity of a generating station are the main concern of those in operating divisions. On the other hand, issues of a broader nature, such as the influence of external effects on dispersion, are considered by the Research Division. However, meteorological information is a general requirement of these applications. At present, continuous measurements are not available at some particular sites because of the sparsity of the observational network. Special monitoring programs or, as discussed here, mesoscale models may be used to overcome this difficulty.

2.2 Intermittent Emission Control

Intermittent emission controls are implemented at the Lakeview and Lambton TGS's. When a high pollution potential period is identified, the load at Lakeview TGS is reduced and low-sulfur coal is burned at Lambton TGS in order to maintain desirable air quality in the vicinity of the stations and to comply with the air pollution guidelines set by the government.

The present intermittent emission control programs rely on information on (1) meteorological conditions, (2) air quality in the area surrounding the two generating stations and (3) the control actions available. The meteorological conditions are obtained from a variety of sources, including PIBAL-minisondes at Lakeview TGS during the high pollution potential periods. The air quality is determined by a dispersion forecast model and verified by the ground-level SO_2 concentrations obtained by monitors. The pollution potential forecasts are then issued by the duty meteorologist, based on the above data, to the System Control Centre at Richview. Finally, a control action may be scheduled. This is a "nowcasting" system.

Since either the load reduction by rescheduling generation, or the use of low-sulfur coals are expensive, models which can accurately predict the adverse conditions which may lead to an increase in pollution levels, say, twelve hours in advance, would be very useful. This need translates into a requirement to forecast the mesoscale wind and temperature fields.

2.3 Long-Range Transport of Air Pollutants

Long-range transport of air pollutants involves the transportation and diffusion of air pollutants from the source to sensitive receptor regions and their en-route chemical transformation. It can be a mesoscale phenomenon because the spatial scale is usually of the order of hundreds to thousands of kilometers and the temporal scale is of the order of days. Atmospheric conditions such as the diurnal variation of the boundary layer and presence of clouds are very important.

Most existing models of long-range transport are Lagrangian. These models use meteorological data observed at weather stations on a routine basis. These have a spatial scale which is inadequate to resolve mesoscale processes. Recently developed Eulerian models, on the other hand, require detailed atmospheric conditions which are generally not available from routine observations. Thus, accurate prediction of wind and temperature fields in the mesoscale is necessary to either improve the Lagrangian models or apply the Eulerian models.

2.4 Nuclear Environmental Studies

The nuclear environmental studies include site specific assessment of the impact of chronic releases, risk analysis and contingency response to acute releases.

Assessment of the impact of chronic releases involves the determination of derived emission limits of radionuclides such as Tritium, Carbon-14 and Iodine-131 and the evaluation of their concentrations in the atmosphere. The transport, diffusion and deposition of these radionuclides are the main concern to the environmental assessment. Risk analyses are carried out and contingency procedures are being redesigned and scrutinized at nuclear power facilities to respond in the unlikely event of an accident.

At present, training exercises are organized by the Emergency Planning Office of the Ontario Ministry of the Solicitor General. For an exercise, a scenario which includes mesoscale atmospheric conditions as a function of time, is developed in advance. Thus, a mesoscale model could be used to develop such scenarios with greater realism than those corresponding to constant and homogeneous climatic conditions. A mesoscale model incorporating local terrain and meteorological effects could also be used to predict wind directions and atmospheric conditions at a specific site to allow timing of discretionary releases and decision making on protective action. Predictions from a mesoscale model may further provide supporting information for risk assessment and licensing procedures.

2.5 Transmission and Distribution

Ontario Hydro operates a large transmission and distribution system that extends throughout most of the inhabited parts of the Province. This system is affected by mesoscale meteorological phenomena. The frequency of occurrence of extreme wind speed over a potential area has to be known before the design and construction of the system begins. Operating lines and transformers are loaded by taking into account meteorological conditions such as temperature, ventilation, etc. Where transmission facilities are limited, an incentive to operate beyond traditional conservative limits exists. Although the low-frequency oscillation and galloping of the transmission lines induced by high winds and ice accretion are of a smaller scale, adequate prediction of their occurrence is based, to some extent, on mesoscale climatology. Other aspects such as effective control of vegetation under transmission lines using herbicide sprays and the protection of workers who engage in transmission line maintenance and transformer station operation also require mesoscale predictions.

Measurements of such mesoscale information are not routinely available on-site. Thus, measurements from nearby areas are used to infer the climatology. These measurements are generally not located in the immediate vicinity of the transmission and distribution facilities and so may not be representative. A mesoscale model which can provide accurate forecasts, especially of severe storms and high temperature and low ventilation situations, would be useful.

2.6 Summary

As discussed, many potential applications of mesoscale wind and temperature field modelling exist within Ontario Hydro. The applications vary in scale from a few tens of kilometers from the generating station, for intermittent emission control and nuclear contingency response, to several hundreds of kilometers for long-range transport of air pollutants and transmission and distribution facilities. The forecast time is also dependent upon specific applications. For control action and decision making applications, results should be available within about an hour. Furthermore, these applications require that the effects of local terrain and mesoscale circulations on wind fields be included and that a very fine spatial resolution be used.

Taking into consideration the above potential applications within Ontario Hydro, the requirements for a mesoscale wind and temperature model may be summarized as follows:

- The model should be capable of providing both short-range and medium-range predictions, according to the application.

- The model should be capable of providing diagnostic meteorological data in data-sparse areas.

- Ideally, the model should be run from readily available data and should have pre-specified error limits for the results.

3.0 PHYSICAL PROCESSES IMPORTANT TO THE MESOSCALE WIND FIELD

In the mesoscale, winds are governed by a balance of the horizontal pressure gradient force, the surface frictional stress and the rotation of the earth, via the Coriolis force. Processes which alter the existing balance would affect significantly the horizontal and vertical wind velocities. In general, these processes can be classified into two major categories:

(1) Those that are primarily forced by large-scale disturbances, and

(2) Those that are primarily forced by surface inhomogeneities.

The latter can be further divided into three groups: land-lake effects, terrain effects and urban effects.

3.1 Large-Scale Weather Effects

These effects are generated by synoptic scale propagating atmospheric systems. The most important effects are the position and movement of high- and low-pressure systems and air masses.

Generally, the high pressure systems (anticyclones) are associated with fair weather and light winds. Due to the rotation of the earth, the winds circulate clockwise about the high pressure centre in the northern hemisphere. On the other hand, the low pressure systems (cyclones) are associated with poor weather and relatively strong winds and circulate counterclockwise about the centre of the system. Therefore, the large-scale winds, or the so-called geostrophic winds, over an area of interest, can be estimated by the position and movement of the high- and low-pressure systems.

An air mass is a vast body of air in which the conditions of temperature and moisture are much the same at all points in a horizontal direction. The conditions of an air mass may be modified by the surface over which it moves. However, the rate of change is slow and the original conditions of the air mass tend to persist. The atmospheric elements which are important to the wind field, such as stability and turbulence, may then be determined by the nature of the air mass.

Furthermore, the movement of air masses leads to the development of severe mesoscale phenomena. Fronts are the boundaries between two different air masses. A large discontinuity in wind direction and temperature is evident over the frontal area. Squall lines are favoured if there is strong veering in the warm sector region of a cyclone. These phenomena may also affect the wind field on

the mesoscale. Detailed discussion of the dynamics and structure of some mesoscale phenomena can be found in Atkinson (1981) and Anthes (1982).

Therefore, background large-scale weather conditions play significant roles in the development of mesoscale systems. Accordingly, the key meteorological variables needed to generate mesoscale wind fields may be obtained from large-scale information. These variables include the mean winds, resulting from the balance of horizontal pressure gradient and Coriolis forces, and the atmospheric stability which in turn, governs the turbulence and vertical velocity.

3.2 Land-Lake Effects

It is well recognized that the physical and thermal properties of land and water surfaces are different. As shown in Table I, the roughness lengths over land surfaces are larger than those over water surfaces by as much as several orders of magnitude. Thus, when air flows from over lake toward land, a dynamical adjustment, due to the change in surface friction, occurs. The wind speed will be reduced and the wind direction will be retarded. A similar adjustment takes place when air flows from over rough land surfaces to lake surfaces. Usually, the adjustment is not immediate throughout the entire air layer, it is generated at the surface and disperses upward. The depth of this adjusted layer is referred to as an internal boundary layer. The depth of the layer increases with increasing distance downwind from the leading edge of the land-lake interface.

Temperature differences between land and lake surfaces are due to different ways in which these surfaces respond to solar radiation. During the day, land absorbs some of the incoming solar radiation, reflects some of this portion to the atmosphere and releases the remaining in the form of sensible and latent heat into the adjacent air. On the other hand, water absorbs most of the incoming solar radiation, due to its large thermal capacity and ability to transfer the radiation to considerable depths through convection and mixing. As a result, very little increase in surface temperature is exhibited. Being warmer and lighter, the air over the land moves upward and creates a relatively low pressure area. An onshore lake breeze therefore develops at low levels, in response to the horizontal pressure gradient. At night, the process is reversed. Both land and water release heat but the land cools more rapidly than the water. An offshore land-breeze then takes place. Because there is no heat source at night, the land breeze is not as intense as the lake breeze in both velocity and vertical extent. Due to the conservation of mass, returning flows occur in upper levels in both lake and land breezes.

TABLE I

SOME PHYSICAL AND THERMAL PROPERTIES OF THE LAND AND WATER SURFACE

(Oke, 1979)

	Land Surface	Water Surface
Roughness Length (m)		$0.1*10^{-5}$-0.0001
Bare soil	0.001 - 0.01	
Short grass	0.003 - 0.01	
Long grass	0.04 - 0.1	
Specific Heat (J kg^{-1} K^{-1})		$4.18*10^{3}$
Dry soil	$0.8*10^{3}$	
Wet soil	$1.48*10^{3}$	
Heat Capacity (J m^{-3} K^{-1})		$4.18*10^{6}$
Dry soil	$1.28*10^{6}$	
Wet soil	$2.96*10^{6}$	
Thermal Conductivity (W m^{-1} K^{-1})		$4.18*10^{6}$
Dry soil	0.3	
Wet soil	2.2	
Albedo (%)		3.4 - 100
Dry soil	20 - 25	
Wet soil	5 - 14	

In addition to differences in surface roughness and temperature, moisture also shows a strong contrast in air over the land and lake. Under favourable conditions, the excessive moisture may create advection fog along shoreline areas. Similarly, it may cause severe snowstorms in the winter time. As pointed out by Richards and Derco (1963), about one-half of the annual snowfall in the snowbelt area on the lee of Lake Huron is contributed by this type of lake-effect storm.

The intensity of land-lake effects is strongly influenced by large-scale weather conditions. The lake-land breeze circulations are best developed in anticyclonic summer weather. Clear skies and light winds tend to maximize the thermal differentiation between land and lake surfaces. Increased cloudiness and strong winds, on the other hand, modify and obliterate these local winds.

3.3 Terrain Effects

There are two types of terrain effects on the flow of air. Firstly, topographical effects can generate local winds. This occurs in very rough terrain features such as mountains and valleys. Like the land-lake breeze circulations, the major forcing of this local wind is the horizontal pressure gradient generated by differential heating between the ground surface and the air at the same elevation. A large diurnal temperature variation always occurs at the ground surface of slopes and floor of the valley. Therefore, during the day, these areas become heat sources. As a result, the air near the sloping ground becomes warmer and moves toward higher elevation and an anabatic flow occurs. At night, these areas are heat sinks and the air moves down elevated terrain, causing a katabatic flow. Compared to the land-lake breezes, these winds are usually weaker and require much less heat input to generate.

Secondly, topography can modify winds. This is a complex process and depends upon the strength and direction of the air flow. Most commonly, the wind will be deflected by friction of the obstacle on its upwind side, while behind the obstacle, a wake or lee vortex will occur. Considerably more turbulence is therefore expected over complex terrain than over a flat surface. Channelling is another phenomenon which occurs when air flows over a break in a slope.

Again, terrain effects are also influenced by large-scale weather conditions. Slope and valley winds are favoured under anticyclonic weather conditions in summer with clear skies and light wind conditions. It should be realized that terrain effects may affect the local weather. The forced ascending motion and resultant adiabatic cooling will enhance terrain-induced clouds and precipitation on the windward side. Frost hollows and the accumulation of pollutants are examples of other problems due to terrain effects.

3.4 Urban Effects

Urban effects are similar to land-lake effects in that they are the result of differential heating and cooling and surface roughness between urban and rural areas.

Due to urbanization, the natural surface of a city is replaced by concrete, asphalt and other impervious and semi-impervious materials. These materials have higher heat capacities and conductivities but lower water availabilities than vegetation. The net result is a general warming of the urban areas compared to the surrounding rural regions. This excess heat of the urban region is known as the "urban heat island." It is more intense at night than during the daytime.

Under calm or very weak large-scale wind conditions, this urban rural temperature contrast creates a convergent lake-breeze type circulation with inflow toward the city and a return flow from city to country at a higher level (Oke, 1979). This urban circulation may not occur under strong wind conditions.

The urban area may also act as an obstacle to the air flow. The horizontal wind speeds are decelerated in the city near the surface due to frictional drag. This may produce low-level convergence and uplift of the air over the centre of urban areas.

The roughness elements of a city are mainly its buildings. The materials and shape of the buildings enhance the heat storage and thus, thermal and mechanical turbulences. Accordingly, the urban atmosphere usually experiences a weaker diurnal variation of temperature and stability than its rural counterpart.

Situations are further complicated if the city is located in complex terrain or near a large body of water. Effects such as orographic channelling, up and downslope winds and land-lake breezes would all modify the temporal and spatial distributions of the meteorological variables over an urban area.

3.5 Summary

The physical mesoscale processes which are important to wind and temperature fields are induced by either large-scale weather conditions or surface inhomogeneities. The large-scale weather conditions provide information on mean wind direction, wind shear and atmospheric stability which are required to develop mesoscale circulations.

Mesoscale circulations resulting from surface inhomogeneities are mainly due to differential heating and cooling and variation of the terrain features. Examples of the former are lake-land breezes, slope-valley winds and urban circulations. These circulations exhibit diurnal variations. Further, these effects affect relative humidity as well as the wind and temperature on the mesoscale. Consequently, climatic elements such as clouds and precipitation and also air quality would be affected.

Therefore, forecasting their onset, strength and duration is important. The mesoscale model, chosen for possible implementation and development, should be able to predict these effects.

4.0 REVIEW OF SOME EXISTING MESOSCALE MODELS

4.1 Model Selection Criteria

The principal criteria used to select models for the present review were the following:

- The model should be three-dimensional.

- The model should have been described in the open literature.

- The model-predicted results should have been compared with field data.

- The model should address scientifically the mesoscale phenomena likely to be of particular interest to Ontario Hydro.

4.2 The Sherman Mass Conservative Model

The model of Sherman (1978), known as MATHEW, is a non-divergent, mass-adjusted wind field model. It is the modified form of the two-dimensional mass consistent flux model (MASCON) of Dickerson (1978). The modification was based upon a variational technique developed by Sasaki (1970), in which the variational formalism defines an integral function whose extremal solution minimizes the variance of the difference between the initial and adjusted or updated values of a variable, subject to physical constraints.

In MATHEW, the principal physical constraint is the conservation of mass for an incompressible flow.

The equation of continuity for the air flow is therefore given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (4\text{-}2\text{-}1)$$

where u, v and w are the adjusted velocity components in the x,y and z directions, respectively.

The variational function used to minimize the error variance between the initial values and the adjusted values may be expressed by:

$$I = \iiint_{x,y,z} \left\{ \alpha_1^2 (u - u_o)^2 + \alpha_1^2 (v - v_o)^2 + \alpha_2^2 (w - w_o)^2 + \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right\} dx\, dy\, dz \qquad (4\text{-}2\text{-}2)$$

where u_o, v_o and w_o are the initial values of u,v, and w, respectively. λ is the Lagrange multiplier and α_1 and α_2 are Gauss precision moduli corresponding to the horizontal and vertical velocities, respectively. α_1 and α_2 are functions of observation errors and/or deviations of the observed wind field from the desired adjusted wind field. Identical Gauss precision moduli are used for the horizontal directions.

The Euler-Lagrange equations associated with the minimization of the variational function are:

$$u = u_o + \frac{1}{2\alpha_1^2}\frac{\partial \lambda}{\partial x} \qquad (4\text{-}2\text{-}3)$$

$$v = v_o + \frac{1}{2\alpha_1^2}\frac{\partial \lambda}{\partial y} \qquad (4\text{-}2\text{-}4)$$

$$w = w_o + \frac{1}{2\alpha_2^2}\frac{\partial \lambda}{\partial z} \qquad (4\text{-}2\text{-}5)$$

and Equation (4-2-1).

The equation for λ can be derived by substituting Equations (4-2-3) to (4-2-5) into (4-2-1)

$$\frac{\partial^2 \lambda}{\partial x^2} + \frac{\partial^2 \lambda}{\partial y^2} + \left(\frac{\alpha_1}{\alpha_2}\right)^2 \frac{\partial^2 \lambda}{\partial z^2} = -\varepsilon \cdot 2\alpha_1^2. \qquad (4\text{-}2\text{-}6)$$

where ε is the error variance of the initial wind field given by:

$$\frac{\partial u_o}{\partial x} + \frac{\partial v_o}{\partial y} + \frac{\partial w_o}{\partial z} = \varepsilon \qquad (4\text{-}2\text{-}7)$$

With proper boundary conditions the value of λ may be obtained by solving Equation (4-2-6) and subsequently, the adjusted mass-consistent velocity field may be calculated by Equations (4-2-3) to (4-2-5).

MATHEW has been applied to provide the three-dimensional wind field for several tracer release studies. As concluded by Lange (1978), the MATHEW-ADPIC results were within a factor of 2 in 50% of the comparisons with field data and within an order of magnitude for 90% of the tests. Except near topographic barriers, the rms adjustments of the model calculations were 10% in wind speed and 5 to 10 degrees in wind direction.

In summary, MATHEW is a diagnostic model. Its computation time is generally reasonable if an iterative procedure such as the successive over-relaxation method is used. For example, the model requires only a few minutes of CPU time on a CDC 7600 system to produce a 25*33*28 grid-point simulation. However, a large temporary storage space, of about several times the number of grid points, is needed to facilitate the complexity of the topography and input information.

The accuracy of the model prediction depends on the initial mean wind conditions. For MATHEW, this initial mean wind field is determined by an interpolation scheme using information available at some reference sites. The vertical velocity is calculated by a power law. This approach is considered inadequate over non-uniform terrain areas.

As seen from Equation (4-2-6), the adjustment process is sensitive to the value chosen for (α_1^2/α_2^2). If (α_1^2/α_2^2) approaches infinity, more of the error associated with the initial mass imbalance is translated directly into the vertical velocity field. On the other hand, if (α_1^2/α_2^2) approaches zero, the initial mass imbalance is reduced to zero by adjusting only the horizontal fluxes. Thus, the values of (α_1^2/α_2^2) have to be determined adequately.

Finally, MATHEW uses only the equation of continuity as a constraint. In other words, the adjustment is only made to the velocity field. Other possible constraints are the three equations of motion simplified by the hydrostatic assumption, the thermodynamic equation and the equation of state. In this case, the initial or the observed values of velocity, temperature, pressure and density fields have to be adjusted, subject to the proper constraints, by expanding the variational technique. Though the MATHEW model formulation can readily be extended to include these physical and dynamic solution constraints (Sherman, 1978), it is thought that the variational function then becomes very complex and results in non-trivial Euler-Lagrange equations whose solution may result in numerical instabilities due to non-linearity. Also, the computer facility may impose other problems making it not practical or economical to use such a variational approach.

4.3 The Pielke Sea-Breeze Model

The model of Pielke (1974) is a time-dependent, hydrostatic and primitive equations model. The model consists of the three-dimensional equations of motion, incompressible continuity equation and the first law of thermodynamics.

Assuming the dependent variables can be expressed by

$$A=\hat{A}+\tilde{A}+A', \qquad (4\text{-}3\text{-}1)$$

where A represents any one of the dependent variables (u,v,w,θ,p). The component A' represents values on a scale that is too small to be resolved explicitly by the model grid and whose effects must be parameterized, while the component $\hat{A}$ represents a synoptic scale value and the component $\tilde{A}$ represents grid-volume averaged perturbations from the synoptic state.

The model equations are

$$\frac{\partial \bar{u}}{\partial t} = -(\hat{u}+\bar{u})\frac{\partial \bar{u}}{\partial x} - (\hat{v}+\bar{v})\frac{\partial \bar{u}}{\partial y} - \bar{w}\frac{\partial}{\partial z}(\bar{u}+\hat{u})$$
$$-\hat{\theta}\frac{\partial \bar{\pi}}{\partial x} - fv_g\frac{\bar{\theta}}{\hat{\theta}} + f'\bar{v} - f'\bar{w} + \frac{\partial}{\partial x}K_H^{(m)}\frac{\partial \bar{u}}{\partial x}$$
$$+\frac{\partial}{\partial y}K_H^{(m)}\frac{\partial \bar{u}}{\partial y} + \frac{\partial}{\partial z}\left[(\hat{K}_s^{(m)}+\bar{K}_s^{(m)})\frac{\partial \bar{u}}{\partial z}\right]$$
$$+\frac{\partial}{\partial z}\left[\bar{K}_s^{(m)}\frac{\partial \hat{u}}{\partial z}\right] \qquad (4\text{-}3\text{-}2)$$

$$\frac{\partial \bar{v}}{\partial t} = -(\hat{u}+\bar{u})\frac{\partial \bar{v}}{\partial x} - (\hat{v}+\bar{v})\frac{\partial \bar{v}}{\partial y} - \bar{w}\frac{\partial}{\partial z}(\bar{v}+\hat{v})$$
$$-\hat{\theta}\frac{\partial \bar{\pi}}{\partial y} + fu_g\frac{\bar{\theta}}{\hat{\theta}} - f\bar{u} + \frac{\partial}{\partial x}K_H^{(m)}\frac{\partial \bar{v}}{\partial x}$$
$$+\frac{\partial}{\partial y}K_H^{(m)}\frac{\partial \bar{v}}{\partial y} + \frac{\partial}{\partial z}\left[(\hat{K}_s^{(m)}+K_s^{(m)})\frac{\partial \bar{v}}{\partial z}\right]$$
$$+\frac{\partial}{\partial z}\left[\bar{K}_s^{(m)}\frac{\partial \hat{v}}{\partial z}\right] \qquad (4\text{-}3\text{-}3)$$

$$\frac{\partial \bar{\theta}}{\partial t} = -(\hat{u}+\bar{u})\frac{\partial \bar{\theta}}{\partial x} - (\hat{v}+\bar{v})\frac{\partial \bar{\theta}}{\partial y} - \bar{w}\frac{\partial}{\partial z}(\bar{\theta}+\hat{\theta})$$
$$+\frac{\partial}{\partial x}K_H^{(\theta)}\frac{\partial \bar{\theta}}{\partial x} + \frac{\partial}{\partial y}K_H^{(\theta)}\frac{\partial \bar{\theta}}{\partial y} + \frac{\partial}{\partial z}\left[(\hat{K}_s^{(\theta)}+\bar{K}_s^{(\theta)})\frac{\partial \bar{\theta}}{\partial z}\right] + \frac{\partial}{\partial z}\left[\bar{K}_s^{(\theta)}\frac{\partial \hat{\theta}}{\partial z}\right] \qquad (4\text{-}3\text{-}4)$$

$$\frac{\partial \bar{w}}{\partial z} = -\left(\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y}\right) \qquad (4\text{-}3\text{-}5)$$

$$\frac{\partial \bar{\pi}}{\partial z} = g\bar{\theta}/\hat{\theta}^2. \qquad (4\text{-}3\text{-}6)$$

and

$$\pi = c_p\left(\frac{\hat{p}}{p_0}\right)^{R/c_p} \qquad (4\text{-}3\text{-}7)$$

where θ is the atmospheric potential temperature, u_g and v_g are the two components of geostrophic wind. $K_H^{(m)}$ and $K_z^{(m)}$ are the horizontal and vertical eddy exchange coefficients for momentum respectively. $K_H^{(\theta)}$ and $K_z^{(\theta)}$ are the horizontal and vertical eddy exchange coefficients for heat, respectively. g is the acceleration of gravity, π is a non-dimensional pressure variable, C_p is the specific heat of dry air at constant pressure, R is the gas constant and p_o is a reference pressure.

The synoptic winds are obtained from the balance of the pressure gradient, Coriolis and eddy friction forces.

$$0=\frac{\partial}{\partial z}\left[\hat{K}_z^{(m)}\frac{\partial \hat{u}}{\partial z}\right]+f(\hat{v}-v_g) \qquad (4\text{-}3\text{-}8)$$

$$0=\frac{\partial}{\partial z}\left[\hat{K}_z^{(m)}\frac{\partial \hat{v}}{\partial z}\right]+f(u_g-\hat{u}), \qquad (4\text{-}3\text{-}9)$$

The synoptic potential temperature is assumed constant in the surface and specified aloft. The model is closed and solvable by specifying distributions of eddy exchange coefficients. It should be noted that the eddy exchange coefficients are calculated independently for vertical and horizontal directions, as well as for momentum and heat fluxes.

The model has been applied to study various mesoscale situations. Examples are the sea breeze circulation in Southern Florida by Pielke (1974); the sea breeze circulations over the Chesapeake Bay area by Segal and Pielke (1981); the wind energy potential in Central Israel by Segal et al (1982).

Various improvements have also been made to the original model in recent years. The topography was included by using a terrain following coordinate system (Mahrer and Pielke, 1975). A heat budget equation was introduced to calculate the surface temperature (Mahrer and Pielke, 1976). Deardorff's (1974) rate equation for the mixed layer height was implemented to close the parameterization scheme for vertical turbulent mixing in the planetary boundary layer (Pielke and Mahrer, 1975). More recently, the model was further modified for environmental assessment applications (Pielke et al, 1983) and an attempt was made to include cumulus parameterization. However, all these improvements increase the dependence of the model on large computer facilities. At present, the model requires about 84 minutes of CPU time to produce a 12-hour simulation over a region of 33*36*11 grid points with a time step of 30 seconds on the NCAR CRAY system.

4.4 The Tapp and White Non-Hydrostatic Model

The Tapp and White (1976) model is a time-dependent and primitive equations model. The basic dynamical equations are the three equations of motion, the continuity equation and the thermodynamic equation. The main aspect of this model is the compressible form of the continuity equation; thus, the non-hydrostatic pressure term can be included in the governing equations.

With the usual notation the equations are

$$\frac{\partial u}{\partial t}+c_p\theta_0\frac{\partial P_1}{\partial x}=-\mathbf{v}.\nabla u+fv-c_p\theta_1\frac{\partial P_1}{\partial x}+F_1 \qquad (4\text{-}4\text{-}1)$$

$$\frac{\partial v}{\partial t}+c_p\theta_0\frac{\partial P_1}{\partial y}=-\mathbf{v}.\nabla v-fu-c_p\theta_1\frac{\partial P_1}{\partial y}+F_2 \qquad (4\text{-}4\text{-}2)$$

$$\frac{\partial w}{\partial t}+c_p\theta_0\frac{\partial P_1}{\partial z}=-\mathbf{v}.\nabla w+g\frac{\theta_1}{\theta_0}-c_p\theta_1\frac{\partial P_1}{\partial z}+F_3 \qquad (4\text{-}4\text{-}3)$$

$$c_p\theta_0\frac{\partial P_1}{\partial t}-gw+c_0^2\nabla.\mathbf{v}=-c_p\theta_0\left[\mathbf{v}.\nabla P_1+(\gamma-1)P_1\nabla.\mathbf{v}-\frac{(\gamma-1)Q}{c_p(\theta_0+\theta_1)}\right] \qquad (4\text{-}4\text{-}4)$$

$$\frac{\partial\theta_1}{\partial t}=-\mathbf{v}.\nabla\theta_1+\frac{Q}{c_p(P_0+P_1)} \qquad (4\text{-}4\text{-}5)$$

where V is the three-dimensional velocity vector and P is a non-dimensional pressure variable given by

$$P=(p/p_s)^{R/C_p} \qquad (4\text{-}4\text{-}6)$$

where p_s is a constant reference pressure. The subscripts 0 and 1 denote values for a steady neutrally stable state of the atmosphere and their corresponding deviations, respectively. F_1, F_2, F_3 and Q are the sources and sinks of the three components of momentum and heat, C_s is the speed of sound in the basic atmosphere and $\gamma = C_p/C_v$, where C_v is the specific heat of dry air at constant volume.

The model has been applied to study sea breeze circulations in Southern Florida (Tapp and White, 1976) and in Southern England (Carpenter, 1979). As well, it has been used to investigate the Hampstead storm, which occurred on August 14, 1975, by Bailey et al (1981). The predicted results have compared favourably to the observations.

As noted from the governing equations, the model allows the propagation of sound waves. The sound wave is the fastest wave in

the atmosphere. Its presence in the equations may produce numerical instability and as a result, a very small time step has to be used (Dutton and Fichtl, 1969). According to Tapp and White (1976), this problem was overcome by using a semi-implicit numerical scheme. With this scheme, the model equations reduced to a set of Helmholtz-type equations which can be solved by direct methods (Tapp, 1976). The implicit scheme is generally unconditionally stable; thus, an arbitrarily large time step may be used, in principle. But in this model, a time step of 90 seconds was used.

The model in its original form contains no physical parameterization, apart from surface friction and diffusion, and it does not include topography. Subsequently, the non-hydrostatic pressure term is mainly generated by thermal convection. Some of these shortcomings have been dealt with recently. For example, the orographic effects were included by changing the model levels to follow the earth's surface (Carpenter and Tapp, 1977). A 1.5 order turbulence scheme was implemented to replace the simple K theory for subgrid mixing (Bailey et al, 1981).

With these modifications, the model may be adapted for practical applications. However, the model requires more computer core storage and execution time than a hydrostatic model because of the non-hydrostatic pressure calculations. The model at present requires 30 minutes of CPU time to generate a 24-hour forecast over a domain of 62 * 61 * 10 grid points with a time step of 90 seconds on a CYBER 205 system.

4.5 The Bornstein Vorticity Streamfunction Model

The model of Bornstein (1985), known as URBMET, is a time-dependent, vorticity-streamfunction model. The model separates the atmospheric boundary layer into two vertical layers: a constant flux surface layer, in which mean field variables are one-dimensional and analytic, and an upper transition layer, in which the atmospheric variables are expressed by the hydrodynamic and thermodynamic equations.

It is also assumed that in the transition layer, the atmosphere is Boussinesq, incompressible and hydrostatic. With these assumptions the transition layer equations may be written as

$$\frac{\partial u}{\partial t}+\frac{\partial (uu)}{\partial x}+\frac{\partial (vu)}{\partial y}+\frac{\partial (wu)}{\partial z}=-\frac{1}{\rho_o}\frac{\partial p_M}{\partial x}+f(v-v_g)+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+K_H\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (4\text{-}5\text{-}1)$$

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}+\frac{\partial (wv)}{\partial z}=-\frac{1}{\rho_o}\frac{\partial p_M}{\partial y}-f(u-u_g)+\frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right)+K_H\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad (4\text{-}5\text{-}2)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (4\text{-}5\text{-}3)$$

$$0=-\frac{1}{\rho_a}\frac{\partial p_M}{\partial z}+g\frac{(T_M+T_n)}{\theta_a} \qquad (4\text{-}5\text{-}4)$$

$$\frac{\partial \theta}{\partial t}+\frac{\partial(u\theta)}{\partial x}+\frac{\partial(v\theta)}{\partial y}+\frac{\partial(w\theta)}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial \theta}{\partial z}\right)+K_H\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}\right)+\frac{1}{\rho_a c_p}\frac{\partial Q_N}{\partial z} \qquad (4\text{-}5\text{-}5)$$

where

$$u_g=\frac{-1}{\rho_a f}\frac{\partial p_n}{\partial y} \qquad (4\text{-}5\text{-}6)$$

$$v_g=\frac{1}{\rho_a f}\frac{\partial p_n}{\partial x} \qquad (4\text{-}5\text{-}7)$$

define the x and y components of a constant geostrophic wind, respectively. The subscripts a, M and n represent the average, mesoscale and synoptic scale values, respectively. K_m and K_h are the vertical eddy exchange coefficients for momentum and heat, respectively, while K_H is the horizontal eddy exchange coefficient and Q_N is the net radiation.

To simplify this set of equations, the three-dimensional vorticity vector and streamfunction are introduced. The relative vorticity vector $\vec{\Omega}$ is defined by

$$\vec{\Omega}=\nabla\times\vec{V}. \qquad (4\text{-}5\text{-}8)$$

If $\vec{\Omega}=(-\xi, \zeta, \nu)$, then

$$\xi=\frac{\partial v}{\partial z}-\frac{\partial w}{\partial y} \qquad (4\text{-}5\text{-}9)$$

$$\zeta=\frac{\partial u}{\partial z}-\frac{\partial w}{\partial x} \qquad (4\text{-}5\text{-}10)$$

$$\nu=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}. \qquad (4\text{-}5\text{-}11)$$

The velocity $\vec{V}$ is related to the streamfunction $\vec{\Psi}$ by

$$\vec{V} = \nabla \times \vec{\Psi} \tag{4-5-12}$$

Again, if $\vec{\Psi} = (\phi, -\psi, 0)$, then

$$u = \frac{\partial \psi}{\partial z} \tag{4-5-13}$$

$$v = \frac{\partial \phi}{\partial z} \tag{4-5-14}$$

$$w = -\left(\frac{\partial \psi}{\partial x} + \frac{\partial \phi}{\partial y}\right). \tag{4-5-15}$$

By using the hydrostatic approximation

$$\xi = \frac{\partial v}{\partial z} = \frac{\partial^2 \phi}{\partial z^2} \tag{4-5-16}$$

$$\varsigma = \frac{\partial u}{\partial z} = \frac{\partial^2 \psi}{\partial z^2}. \tag{4-5-17}$$

the dynamic equations for ξ and ς may be obtained by differentiating Equations (4-5-1) and (4-5-2) with respect to the vertical coordinate z and Equations (4-5-4) once with respect to x and once with respect to y and then combining the resulting equations:

$$\frac{\partial \xi}{\partial t} = -\frac{\partial (u\xi)}{\partial x} - \frac{\partial (v\xi)}{\partial y} - \frac{\partial (w\xi)}{\partial z} + \xi \frac{\partial u}{\partial x} - \varsigma \left(f + \frac{\partial v}{\partial x}\right) + \frac{g}{\theta_a} \frac{\partial \theta_M}{\partial y} + \frac{\partial^2}{\partial z^2}(K_m \xi) + K_H \left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2}\right) \tag{4-5-18}$$

$$\frac{\partial \varsigma}{\partial t} = -\frac{\partial (u\varsigma)}{\partial x} - \frac{\partial (v\varsigma)}{\partial y} - \frac{\partial (w\varsigma)}{\partial z} + \varsigma \frac{\partial v}{\partial y} + \xi \left(f - \frac{\partial u}{\partial y}\right) + \frac{g}{\theta_a} \frac{\partial \theta_M}{\partial x} + \frac{\partial^2}{\partial z^2}(K_m \varsigma) + K_H \left(\frac{\partial^2 \varsigma}{\partial x^2} + \frac{\partial^2 \varsigma}{\partial y^2}\right). \tag{4-5-19}$$

By this procedure, the transition layer equations are Equations (4-5-5) and (4-5-13) to (4-5-19).

The two-dimensional version of this model has been applied to study the idealized night time situation of an urban boundary layer (Bornstein, 1975) and SO_2 concentrations in Venice, Italy (Bornstein and Runca, 1977). The three-dimensional version, on the other hand, has been used to simulate sea breeze circulations in the coastal urban environment of New York City (Bornstein, et al, 1984). The predicted results demonstrated most of the qualitative features of the time varying pollutant concentrations and sea breeze flow conditions.

The application of the vorticity-streamfunction approach can reduce the number of dynamical equations in the model and in particular, eliminate the pressure field from the equations of motion. Thus, such a model requires less computational time than the primitive equations model. For the two-dimensional version, the model needs 7 minutes CPU time for an 18-hour simulation on a CDC 7600 system. For the three-dimensional version, the model requires 24 minutes of CPU time to generate a 24-hour forecast over a domain of 40*30*10 grid points on an IBM 3081 system.

However, no topography is incorporated into the model and the accuracy of the model depends upon the K profiles used to specify the turbulence. The areas need improvement.

4.6 The NCAR Mesoscale Model

The NCAR mesoscale model is a time-dependent, hydrostatic, primitive equations model. It was originally developed by Anthes and Warner (1978). The model is formulated using a terrain-following σ coordinate on a Lambert conformal map projection. σ is given by

$$\sigma = \frac{p - p_t}{p_s - p_t} = \frac{p - p_t}{p^*} \qquad (4\text{-}6\text{-}1)$$

where p is pressure, p_t is the pressure at the top of the model and p_s is the surface pressure. The map scale factor is

$$m = \frac{\sin\psi_1}{\sin\psi}\left[\frac{\tan(\psi/2)}{\tan(\psi_1/2)}\right], \qquad (4\text{-}6\text{-}2)$$

where ψ_1 is 30°, and ψ is colatitude.

The flux form of the momentum equations may be written

$$\frac{\partial p^* u}{\partial t} = -m^2\left[\frac{\partial(p^* uu/m)}{\partial x} + \frac{\partial(p^* vu/m)}{\partial y}\right] - \frac{\partial p^* u\dot{\sigma}}{\partial \sigma}$$
$$-mp^*\left[\frac{RT}{(p^* + p_t/\sigma)}\frac{\partial p^*}{\partial x} + \frac{\partial \phi}{\partial x}\right] + p^* v f + F_u \qquad (4\text{-}6\text{-}3)$$

$$\frac{\partial p^* v}{\partial t} = -m^2\left(\frac{\partial p^* uv/m}{\partial x} + \frac{\partial p^* vv/m}{\partial y}\right) - \frac{\partial p^* v\dot{\sigma}}{\partial \sigma}$$

$$-mp^*\left[\frac{RT}{(p^*+p_t/\sigma)}\frac{\partial p^*}{\partial y} + \frac{\partial \phi}{\partial y}\right] - p^* u f + F_v \qquad (4\text{-}6\text{-}4)$$

where $\dot{\sigma} = \frac{d\sigma}{dt}$. The vertical velocity ω is related to $\dot{\sigma}$ by

$$\omega = p^*\dot{\sigma} + \sigma\frac{dp^*}{dt}, \qquad \frac{dp^*}{dt} = \frac{\partial p^*}{\partial t} + m\left(u\frac{\partial p^*}{\partial x} + v\frac{\partial p^*}{\partial y}\right). \qquad (4\text{-}6\text{-}5)$$

The terms F_u and F_v represent the horizontal redistribution of momentum by small-scale turbulent eddies.

The continuity equation is

$$\frac{\partial p^*}{\partial t} = -m^2\left(\frac{\partial p^* u/m}{\partial x} + \frac{\partial p^* v/m}{\partial y}\right) - \frac{\partial p^*\dot{\sigma}}{\partial \sigma} - \frac{2wp^*}{a}. \qquad (4\text{-}6\text{-}6)$$

The advective form of the thermodynamic equation may be written

$$\frac{\partial p^* T}{\partial t} = -m^2\left(\frac{\partial up^* T/m}{\partial x} + \frac{\partial vp^* T/m}{\partial y}\right) - \frac{\partial p^* T\dot{\sigma}}{\partial \sigma}$$

$$+\frac{RT\omega}{c_p(\sigma+p_t/p^*)} + \frac{p^* Q}{c_p} + F_t, \qquad (4\text{-}6\text{-}7)$$

Here, Q represents thermal energy sources and sinks, and F_t represents horizontal redistribution of thermal energy by small-scale eddies. Geopotential is diagnosed from the hydrostatic equation

$$\frac{\partial \phi}{\partial \ln(\sigma+p_t/p^*)} = -RT. \qquad (4\text{-}6\text{-}8)$$

The model has been applied to study several mesoscale phenomena such as sea breeze circulations (Warner et al, 1978), mesoscale convective systems (Anthes et al, 1982) and flow over mountains (Seaman and Anthes, 1981).

This model has certain advantages. It employs the semi-implicit numerical scheme. As discussed before, this scheme allows the model to use a time step longer than for a similar explicit case.

The model uses a terrain-following coordinate system and a map projection to deal with variable terrain and produces the least distortion for middle latitude areas.

The surface temperature is determined by solving an energy budget equation. The budget equation is capable of providing diurnal variations of convective activity and thermal discontinuity between different surface features. The model is designed to use either a computationally efficient, bulk parameterization of the boundary layer for situations in which the detailed behaviour of the boundary layer is of secondary interest or a high-resolution boundary layer physics when a detailed description of the boundary layer is needed. Furthermore, the model contains a modified Kuo-type scheme to parameterize cumulus convections.

The disadvantage of the model is its complexity and high computational cost. A 24-hour simulation of a typical sea breeze circulation over a region of 50*50*10 grid points with a time step of 200 seconds requires 7 minutes of CPU time on the CRAY 1A system. This is probably not practical for application within Ontario Hydro.

4.7 The Ontario Ministry of the Environment Model

The Ontario Ministry of the Environment (OME) model is a time-dependent, primitive equations model developed by Maddukuri and Slawson (1984). The topography is incorporated into the model by using a vertical coordinate given by

$$z_* = z - h(x,y) \qquad (4\text{-}7\text{-}1)$$

where z is the vertical coordinate in the Cartesian coordinate system and h is the elevation of the surface. The model also uses the hydrostatic approximation and a non-dimensional pressure variable

$$P = \left(\frac{p}{p_o} \right)^{R/C_p} \qquad (4\text{-}7\text{-}2)$$

With these assumptions, the model equations may be written as

$$\frac{\partial u}{\partial t} = - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w_* \frac{\partial u}{\partial z_*} + f v - g \frac{\partial h}{\partial x} - c_p \theta \frac{\partial}{\partial x} (P)$$

$$+ \frac{\partial}{\partial z_*} (K_{mz} \frac{\partial u}{\partial z_*}) + \frac{\partial}{\partial x} (K_{mx} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (K_{my} \frac{\partial u}{\partial y}), \qquad (4\text{-}7\text{-}3)$$

$$\frac{\partial v}{\partial t} = - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w_* \frac{\partial v}{\partial z_*} - f u - g \frac{\partial h}{\partial y} - c_p \theta \frac{\partial}{\partial y} (P)$$

$$+ \frac{\partial}{\partial z_*} (K_{mz} \frac{\partial v}{\partial z_*}) + \frac{\partial}{\partial x} (K_{mx} \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y} (K_{my} \frac{\partial v}{\partial y}), \qquad (4\text{-}7\text{-}4)$$

$$\frac{\partial \theta}{\partial t} = - u \frac{\partial \theta}{\partial x} - v \frac{\partial \theta}{\partial y} - w_* \frac{\partial \theta}{\partial z_*} + \frac{\partial}{\partial z_*} (K_{\theta z} \frac{\partial \theta}{\partial z_*}) + \frac{\partial}{\partial x} (K_{\theta x} \frac{\partial \theta}{\partial x}) \qquad (4\text{-}7\text{-}5)$$

$$+ \frac{\partial}{\partial y} (K_{\theta y} \frac{\partial \theta}{\partial y}),$$

$$u \frac{\partial P}{\partial x} + v \frac{\partial P}{\partial y} + w_* \frac{\partial P}{\partial z_*} - P(\gamma-1) [u \frac{\partial (\ln \theta)}{\partial x}$$

$$+ v \frac{\partial (\ln \theta)}{\partial y} + w_* \frac{\partial (\ln \theta)}{\partial z_*}] = (\gamma-1) P (\nabla . v), \qquad (4\text{-}7\text{-}6)$$

$$\frac{\partial P}{\partial z_*} = - \frac{g}{c_p \theta}, \qquad (4\text{-}7\text{-}7)$$

where $w_* = dz_*/dt$ which is related to the vertical velocity w by

$$w = u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} + w_* \qquad (4\text{-}7\text{-}8)$$

The model has been used to simulate the wind field over the region of Metropolitan Toronto on June 11, 1973. Results were compared with those observed by a micrometeorological observational network operated by the Atmospheric Environment Service of Canada.

The model was designed to take into account different horizontal and vertical eddy exchange coefficients. For the above simulation, the horizontal eddy exchange coefficients were assumed to be constant and to have a value of 1000 $m^2 s^{-1}$. The vertical components, on the other hand, were parameterized differently in the regions above and below the 50-m level. This 50-m level was used as the top of the surface layer in the two-dimensional version of the model (Maddukuri et al, 1978). However, in the three-dimensional version, the surface layer is not specified. The dynamical equations are used throughout the entire planetary boundary layer.

It seems that the use of the 50-m level is not appropriate in this case. The latest modification of the model is to include the surface heat flux into the eddy exchange coefficient parameterizations and to use a rate equation to determine the boundary layer height. At present, the model requires 25 minutes of CPU time to generate a 24-hour forecast over a domain of 20*16*12 grid points with a time step of 120 s on an IBM 370 system.

4.8 The Lee and Kau Complex Terrain Model

The model of Lee and Kau (1984) is a diagnostic model. It is a compromise between hydrodynamic and objective analysis wind models. The surface wind fields are obtained by

$$V = V_B + V_D, \tag{4-8-1}$$

where V_D is the drainage wind component due to surface cooling in sloping terrain and V_B is the boundary layer wind departure from the drainage wind. The drainage wind component is calculated by

$$V_D = (\Delta_0 N/r)\, e^{-\zeta} \sin\zeta \tag{4-8-2}$$

where Δ_0 is the surface potential temperature deviation, defined as $\Delta_0 = -\theta_0' = \theta_0 - \bar{\theta}$;

$$N = \left[\frac{gr}{\bar{\theta} - \theta'}\right]^{1/2} \tag{4-8-3}$$

$$r = -\frac{\partial\theta}{\partial z} > 0 \tag{4-8-4}$$

$$\zeta = (n - z_0)/l \text{ is the dimensionless height} \tag{4-8-5}$$

$$l = (2K_m/N \sin\beta)^{1/2} \tag{4-8-6}$$

$$\theta' = -\Delta_0 e^{-\zeta} \cos\zeta \tag{4-8-7}$$

where z_o is a surface roughness length, n is an axis normal to the terrain slope and β is the slope angle. Further, the ground potential temperature θ_0 is determined by solving a surface energy equation and the model makes use of the Businger-Dyer surface layer formulation (Businger et al, 1971).

The three-dimensional wind field is obtained by solving the simplified equations of motion:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = f(v - v_g) + K\frac{\partial^2 u}{\partial z^2}, \qquad (4\text{-}8\text{-}8)$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -f(u - u_g) + K\frac{\partial^2 v}{\partial z^2}, \qquad (4\text{-}8\text{-}9)$$

$$\frac{\partial P}{\partial z} = -\rho g, \qquad (4\text{-}8\text{-}10)$$

$$w = u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} \qquad (4\text{-}8\text{-}11)$$

Here, h is the height of the local terrain. Note that while the vertical velocity obtained from Equation (4-8-11) is valid at lower levels, it becomes less acceptable as height increases. Consequently, a variational formulation suggested by O'Brien (1970) is used to adjust the vertical velocity at upper levels.

The model has been applied to simulate the wind field over the area of the ASCOT (Atmospheric Studies in Complex Terrain) field experiments during July, 1979 near the Geysers geothermal area in California. Predicted results showed that drainage winds are dominant at night. At noon, the flow is upslope.

In summary, this model combines an objective approach to determine the slope wind component due to surface cooling and simplified three-dimensional equations of motion to predict the stationary flow over complex terrain.

Since a statistical interpolation is used, the model requires only one set of input wind and temperature data to generate the calculation. The dynamical equations are time-independent and analytical solutions are possible. As a result, the model is easy to execute and computationally efficient.

However, the model in its present version takes into account only the terrain height and surface roughness as external factors. It also uses a constant K to specify turbulence. It is suspected that the model is valid only for the predictions of air flow over complex terrain. It may not be adequate to predict air flow over a thermal inhomogeneity such as those giving rise to lake breeze circulations.

4.9 Summary

Seven three-dimensional mesoscale wind field models have been reviewed briefly in this section. Table II summarizes the conceptual structures and levels of detail of these reviewed models. As seen from the table, two of the models (Sherman's and Lee and Kau's) are diagnostic. They use mass conservation to minimize

TABLE II

SUMMARY OF REVIEWED MESOSCALE WIND FIELD MODELS

	Sherman	Pielke	Tapp & White	Bornstein	NCAR	OME	Lee & Kau
Conceptual Structure							
Equations	Diagnostic; Incompressible	Prognostic Primitive; Hydrostatic	Prognostic; Primitive; Non-hydrostatic	Prognostic; Vorticity-Stream function; Hydrostatic	Prognostic; Primitive; Hydrostatic	Prognostic Primitive; Hydrostatic	Diagnostic; Primitive; Hydrostatic
Grid Domain	25*33*28	33*36*11	62*61*10	40*30*10	50*50*10	20*16*12	20*14*10
Minimum horizontal resolution	4.3 km	1 km	10 km	1.6 km	1 km	5 km	0.5 km
Vertical resolution	50 m	Variable 5 m at surface 2 km above	Variable 10 m at surface 1.5 km at 12 km	Variable 25 m at surface 300 m above	Variable 500 m at surface 1 km above	Variable	Variable
Coordinate	xyz	xyσ	xyσ	xyz	xyσ	xyz_*	xyz
Solution technique	Successive Over-relaxation	Forward in time; Upstream spline interpolation for advection; Implicit diffusion	Centered in time; Centered in space	Forward in time; Centered in space Fractional different for advection and diffusion	Centered in time; Centered in space	Forward in time; Centered in space; Explicit diffusion	Analytical
Time step	None	30 s	60 s		191 s	120 s	None
Level of Details							
Topography	Yes	Yes	Yes	No	Yes	Yes	Yes
Turbulence	Power law	K profiles	Kinetic energy equation	O'Brien K Formulation	Day: thermal structure Night: local Richardson number	Mixing length formulation	Constant
Surface Heat Flux	None	Prescribed	Energy Budget Equation	Energy & Moisture Budget Equation	Energy & Moisture Budget Equation	Deardorff's predictive formulation	Energy Budget Equation
Radiation	None	Sasamori's formulation	Empirical	Atwater & Brown's formulation	None	Empirical	Swinbank's formulation
Clouds	None	None	None	None	Kuo-type	None	None
Computer time for an example 24 h forecast	few min CDC 7600	168 min CRAY	30 min CYBER 205	24 min IBM 3081	7 min CRAY-1A	25 min IBM 370	Not Available

error between the observed and predicted winds and extrapolate the wind field from reference sites to the entire horizontal grid system. Note that the diagnostic models are those using equations without time-tendency terms. On the other hand, the prognostic models are those with time-dependent equations.

The other models are prognostic. Predictions are obtained by solving mathematical equations which include the relevant physical processes. The hydrostatic approximation is used in all these models except the model of Tapp and White. All models are derived from primitive equations with the exception of the model of Bornstein in which vorticity and streamfunctions, the differentiated forms of the horizontal velocities, are used. Cumulus parameterization is included only in the NCAR mesoscale model.

The next section will discuss the suitability of these models for possible development and application within Ontario Hydro.

5.0 EVALUATION OF REVIEWED MODELS TO ONTARIO HYDRO's REQUIREMENTS

Due to the complexity of the mesoscale wind and temperature fields, the ideal approach to predict these parameters would be to derive them by means of the complete set of hydro- and thermodynamic equations.

Most of Ontario Hydro's generating stations are located in lakeshore areas. There exists a discontinuity of surface roughness and thermal structure between land and lake. This discontinuity may enhance the non-hydrostatic effects to magnitudes which are comparable to those of the hydrostatic. Thus, the hydrostatic assumption may be inadequate for Ontario Hydro's applications.

The topographical features of southern Ontario are, in general, complex. As shown in Figure 1, the region may be considered as a peninsula surrounded by the lower Great Lakes - Ontario, Erie and Huron. The terrain in the region is gently rolling, with the central part rising to an elevation of over 500 m above the mean sea level. Such variations in topography have significant influences on the wind field. For example, mesoscale lee vortex and downslope and upslope winds are likely to occur in this region. Thus, topographical effects should be incorporated in the model formulation, especially for long-range transport and transmission and distribution applications.

The corresponding turbulence characteristics may also be changed due to different surface and thermal features. This should be taken into consideration in determining the turbulent components of the model. Further, practical and economic considerations require that the model should be readily verifiable and the CPU time should be reasonable.

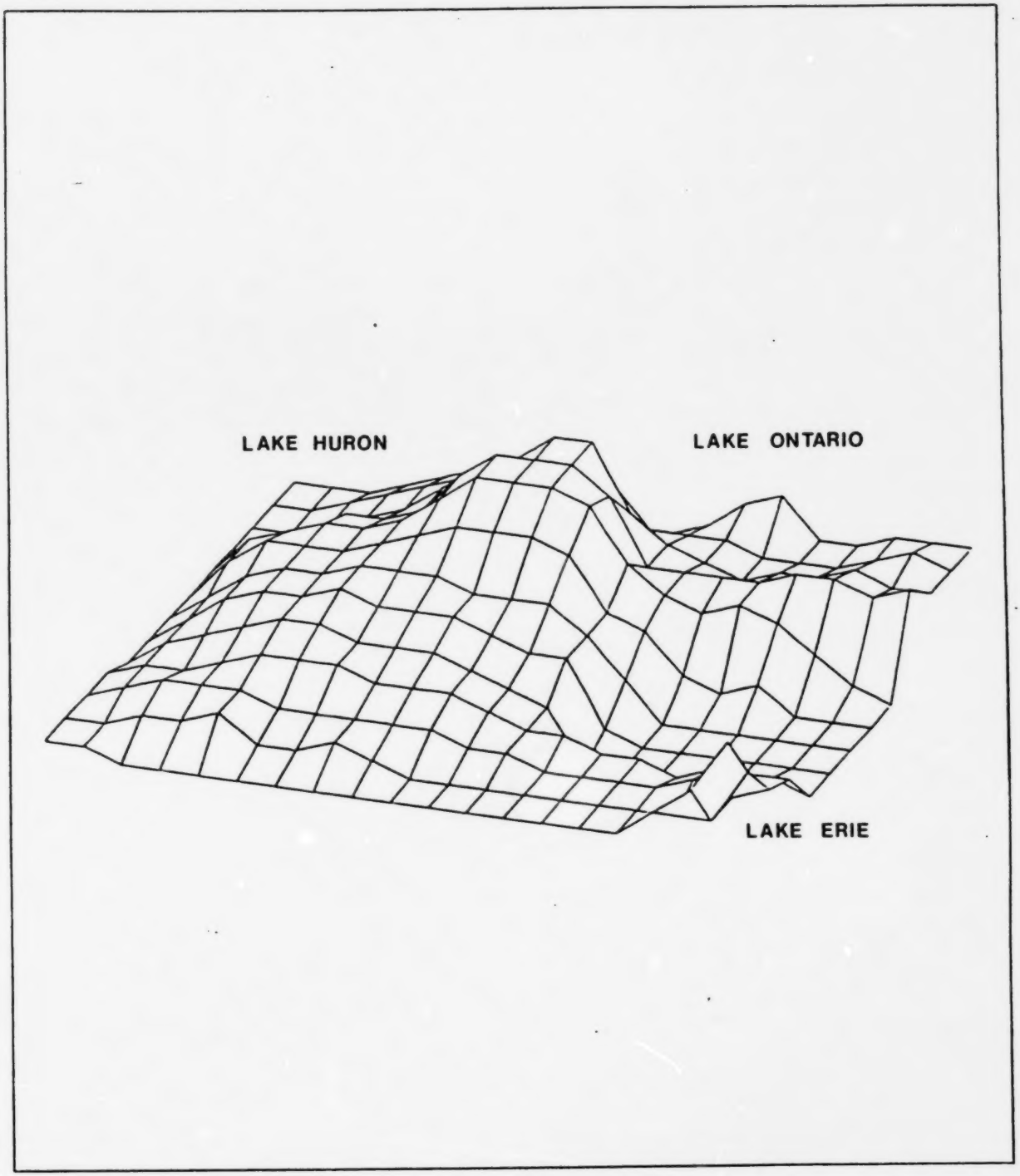

FIGURE 1

Three-dimensional Topographical Features of the Southern Ontario Area. View is taken from an Azimuth Angle of 160° and an Elevation Angle of 20°. The Horizontal Grid Sizes are 10' lat. * 10' long. or 13.3 * 18.5 km

In the light of the above discussions, it is obvious that none of the existing three-dimensional wind field models, as they are, meet these requirements fully. A summary of the evaluation of reviewed models is given in Table III with respect to their potential applications. However, some of the models can be adopted with some modifications if the requirements can be relaxed to a reasonable extent.

Among the models reviewed in the preceding section, Pielke's sea breeze model and the NCAR mesoscale model are considered the most sophisticated ones. Both models employ a complete set of dynamic equations and provide realistic results. However, these two models require an unreasonably large computer facility which makes them not practical for implementation.

TABLE III

EVALUATION OF REVIEWED MESOSCALE WIND FIELD MODELS
(The Number represents relative rankings, the higher the better)

	Sherman	Pielke	Tapp & White	Bornstein	NCAR	OME	Lee & Kau
General Applications							
Lake-land Breeze	2	3	3	2	2	2	1
Air Flow over Complex Terrain	2	2	2	0	3	2	2
Urban Circulation	0	2	2	3	2	2	1
Ontario Hydro Applications							
Environmental Impact and Assessment	2	3	3	2	3	2	1
Intermittent Emission Control	1	2	2	2	2	2	1
Long-Range Transport	1	2	2	1	2	2	1
Nuclear Environmental Studies	1	1	1	1	1	2	1
Transmission and Distribution	1	2	2	1	2	1	1
Total Ranking	10	17	17	12	17	15	9

Bornstein's model uses the vorticity-streamfunction form of the governing equations. The wind field is obtained by integrating vorticities with respect to space. It has the advantage of using less computational time. Drawbacks of the model are that it does not incorporate topography and the elimination of the density and pressure may lead to the loss of some insight into the compressible processes. On the other hand, Lee and Kau's model does not include the diurnal variations of wind and temperature. Therefore, at present, both Bornstein's and Lee and Kau's models are probably not practical here.

The modified version (Carpenter and Tapp, 1977) of Tapp and White's 1976 model is then the most attractive model. The model is non-hydrostatic and uses primitive equations. The topography is incorporated by means of a terrain-following vertical coordinate given by

$$z = z_1 - z_2 \qquad (5\text{-}1)$$

where z_1 is the height above sea level and z_2 is the orographic height. With this coordinate, the model levels are parallel to the ground surface. The boundary layer turbulence is determined by a set of semi-empirical parameterizations which cover the stable and unstable atmospheric conditions. The model also includes horizontal diffusion.

The main drawback of the model is its computing requirements. As discussed before, it requires the solution of a diagnostic equation for pressure at every time step, in addition to the solution of the hydro- and thermodynamic equations. This requires more computer core storage and time than a comparable hydrostatic model needs.

If a coarse grid is used for the calculations, the non-hydrostatic effects may not be important and one might as well use a hydrostatic model. Then, implementation of the OME model becomes viable. However, the formulation of the turbulence parameterizations is an area where improvement is needed. A higher-order closure scheme, similar to that of Yamada (1979), or the sub-grid closure hypothesis of Donaldson (1973), may be useful.

The diagnostic variational model of Sherman (1978) may be computationally competitive with a non-hydrostatic model. It requires only one kinematical constraint - the equation of continuity. If considerable meteorological data are available, the model is suitable to provide objectively-analyzed wind fields. The lack of temperature calculation is the main drawback to the model. However, the temperature field can be obtained by applying the same variational technique as for the wind field but using the thermodynamic equation as a constraint, as follows.

Assuming that the steady-state thermodynamic equation may be written as:

$$u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + w \frac{\partial \theta}{\partial z} - \frac{\partial}{\partial z} \left(K_z \frac{\partial \theta}{\partial z} \right) = 0 \qquad (5\text{-}2)$$

Then,

$$u \frac{\partial \theta_o}{\partial x} + v \frac{\partial \theta_o}{\partial y} + w \frac{\partial \theta_o}{\partial z} - \frac{\partial}{\partial z} \left(K_z \frac{\partial \theta_o}{\partial z} \right) = \epsilon_\theta \qquad (5\text{-}3)$$

where θ_o is the initial potential temperature and ϵ_θ is the error variance of the initial field. The function needed to minimize the variance subject to the thermal constraint is

$$I_\theta = \iiint_{x,y,z} \left[\alpha_\theta^2 (\theta - \theta_o)^2 + \lambda_\theta \left\{ u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + w \frac{\partial \theta}{\partial z} - \frac{\partial}{\partial z} \left(K_z \frac{\partial \theta}{\partial z} \right) \right\} \right] dx\, dy\, dz \qquad (5\text{-}4)$$

Here, α_θ^2 is the Gauss precision modulus and λ_θ is the Lagrangian multiplier. The associated Euler-Lagrange equations are

$$\theta = \theta_o + \Lambda / 2\alpha_\theta^2 \qquad (5\text{-}5)$$

where

$$\Lambda \equiv u \frac{\partial \lambda_\theta}{\partial x} + v \frac{\partial \lambda_\theta}{\partial y} + w \frac{\partial \lambda_\theta}{\partial z} - \frac{\partial}{\partial z} K_z \frac{\partial \lambda_\theta}{\partial z} \qquad (5\text{-}6)$$

and Equation (5-2).

Substituting (5-5) into (5-2) and using (5-3) yields

$$u \frac{\partial \Lambda}{\partial x} + v \frac{\partial \Lambda}{\partial y} + w \frac{\partial \Lambda}{\partial z} - \frac{\partial}{\partial z} \left\{ K \frac{\partial \Lambda}{\partial z} \right\} = - (2\alpha_\theta^2)\ \epsilon_\theta \qquad (5\text{-}7)$$

Thus, Equations (5-7) and (5-6) may be solved for Λ and λ_θ, respectively and subsequently, the adjusted potential temperature field may be calculated by Equation (5-5).

If sufficient meteorological data are not available, the full set of hydro- and thermodynamic equations has to be used as a constraint. In such a case the model may not be computationally feasible.

An alternative approach is to employ another simple model which can generate the surface wind field over the area of interest and then apply the variational technique to adjust the wind field,

subject to the relevant constraint. The Environmental Science Section wind field model can be used for this purpose. The model was originally developed by Danard (1977) and implemented by Tam (1982) within Ontario Hydro. It is horizontally two-dimensional and makes use of the momentum, thermodynamics and hydrostatic equations. The model could be used to produce a "guess" two-dimensional wind and temperature field from available meteorological data. This "guess" two-dimensional field could then be combined with a high resolution one-dimensional boundary layer model, such as that proposed by Blackadar (1979), to yield a "guess" three-dimensional distribution. Finally, this information may be supplied to the Sherman model to generate the adjusted wind and temperature fields. The first part of this proposed approach has been applied to optimize the wind field model for the Pickering area (Tam, 1984). Results are promising.

6.0 CONCLUDING REMARKS

The mesoscale is a scale between the macroscale and the microscale. It has a wide range of horizontal spatial and temporal scales from a few kilometers to several hundred kilometers and about one hour to a few days. Within this scale, not only can severe weather have adverse social and economic impacts on human activity but other phenomena, such as lake-land breezes and terrain and urban effects, are of considerable importance. Of special interest to Ontario Hydro is the mesoscale aspect of air quality in which the mesoscale wind and temperature fields play significant roles.

This report is concerned with the development of a mesoscale model which is able to produce wind and temperature fields for Ontario Hydro's applications. A discussion of potential needs and requirements within Ontario Hydro indicates that the suitable mesoscale wind field model should be capable of providing both short-range and medium-range predictions; should be able to generate diagnostic meteorological data in data-sparse areas; should be run from readily available real time data, and should not require unreasonably large computer facilities.

Winds on the mesoscale are governed by a balance of the horizontal pressure gradient force, the surface frictional stress and the Coriolis force. This balance may be disturbed by processes induced by either synoptic-scale weather patterns or surface inhomogeneities. The latter is particularly important to Ontario Hydro. Therefore, the suitable model should incorporate these mesoscale effects and should be able to predict their onset, intensities and durations.

In view of these requirements, seven recent mesoscale models were reviewed. They are Sherman's mass conservative model, Pielke's sea breeze model, Tapp and White's non-hydrostatic model, Bornstein's vorticity-streamfunction model, NCAR's mesoscale model, OME's wind field model and Lee and Kau's complex terrain

model. All these models are three-dimensional and have been described in the open literature. There are different conceptual structures and levels of detail among these models. These include diagnostic vs prognostic; hydrostatic vs non-hydrostatic; primitive equations vs vorticity-streamfunction; steady vs time-dependent and also one-layer vs two-layers.

On the basis of this review, a three-dimensional non-hydrostatic model incorporating topographical effects meets most of the requirements for potential applications within Ontario Hydro. According to Carpenter (1979), a 24-hour forecast of mesoscale wind and temperature fields could be produced in about half an hour by using advanced vector computers.

A three-dimensional hydrostatic model with terrain effects may be feasible if a coarse grid is used. Another computationally viable alternative to the non-hydrostatic model is the diagnostic variational model such as that of Sherman (1978). As mentioned before, the accuracy of this model depends on the initial mean wind conditions.

Thus, Sherman's model is applicable if sufficient meteorological data are available. The temperature field may be obtained by the same variational technique but using the thermodynamic equation as the constraint.

If the meteorological data are not sufficient, the existing Environmental Science Section wind field model may be used to generate a "guess" two-dimensional wind and temperature field. This "guess" two-dimensional field can be combined with a high resolution boundary layer model to yield a "guess" three-dimensional wind and temperature field. The "guess" three-dimensional field may be supplied to Sherman's model for adjustment, subject to physical and dynamical constraints.

Finally, in order to ensure the reliability and accuracy of a numerical model, procedures called initialization and validation have to be performed. Generally, initialization involves the specification of initial and boundary conditions. The former can be obtained by either using available observational data which are extrapolated to grid points or using idealized, mathematically specified initial data. The boundary conditions can be adjusted according to the application.

Validation of a model can be established by comparing the results predicted by the model with those predicted by known analytic theory and/or from other models which have been developed independently. It can also be made by comparing the model results with observations. The latter is useful for particular applications such as those within Ontario Hydro when point-to-point and pattern-to-pattern correspondences between model predictions and observations are important.

Details of the strategy and procedure for the development and implementation of a suitable model are still to be worked out. This step will await discussions within Ontario Hydro regarding the needs and implications of proceeding with this work.

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